

NEW CONSTRAINTS ON DARK ENERGY

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New Cosmic Microwave Background, Galaxy Clustering and Supernovae type Ia data are increasingly constraining the dark energy component of our Universe. While the cosmological constant scenario remains consistent with these new tight constraints, the data does not rule out the possibility that the equation of state parameter is less than -1

1 Introduction

The recent results of precision cosmology have been extremely important since they provide an excellent agreement with our theoretical picture of the cosmos, incorporating the standard model of structure formation, the inflationary prediction of flatness, the presence of cold dark matter and an amount of baryonic matter consistent with Big Bang Nucleosynthesis constraints (see e.g. ^{1, 2, 3}). The price-tag of this success story concerns a very puzzling consequence: the evolution of the universe is dominated by a mysterious form of energy, X , coined dark energy, (an unclustered negative pressure component of the mass-energy density), with a present-day energy density fraction $\Omega_X \simeq 2/3$ and equation of state parameter (pressure over energy density ratio) $w_X \equiv p_X/\rho_X \sim -1$ (or even $w_X < -1$, see ⁴).

This discovery may turn out to be one of the most important contribution to physics in our generation. Hence it is especially important to consider all possible scheme for dark energy.

A true cosmological constant Λ may be at works here. However, as it is well known, is difficult to associate the small observed value of the cosmological constant $\rho_\Lambda \sim (10^{-3}eV)^4$ with vacuum fluctuations in scalar field theories, which, for example, for bosonic and fermionic fields would led to an effective cosmological constant of $\rho_\Lambda \sim 10^{76}GeV^4$, i.e. of 123 orders of magnitude larger. Moreover, the cosmological constant immediately introduces a “why now” problem, since an extreme fine-tuning of initial conditions is required in order to obtain $\rho_\Lambda \sim \rho_m$ *today*: already at redshift $z \sim 2$ the cosmological constant is subdominant, while at the time of the electroweak phase transition $\rho_\Lambda/\rho_m \sim 10^{-55}$.

Systematics in the data are most probably under control: combined analyses of CMB, LSS and SN-Ia data yield $\Omega_\Lambda = 0.74 \pm 0.04$, i.e. a more than 14σ 's detection. The SN-Ia alone is highly inconsistent with $\Omega_\Lambda = 0$ if one considers flat universes or open with $\Omega_M > 0.1$. The CMB data alone is also inconsistent with $\Omega_\Lambda = 0$ unless one considers closed models with $\Omega_M \sim 1.3$ and a very low Hubble parameter $h \sim 0.4$ which, again, are incompatible with several complementary datasets.

Assuming modifications to the model of structure formation which are not connected with a new form of energy, like, for example, a contribution from isocurvature perturbations, doesn't seem able to mimic Λ or a dark energy component (see e.g. ⁵).

2 Alternatives to Λ

A complete treatment of the possible contenders to the dark energy throne can be found in several and excellent recent reviews (see e.g. ^{6, 7, 8, 9}). The important point is that dark energy candidates have an equation of state parameter which can be different from -1 and varies with time compared to that of a cosmological constant which remains fixed at $w_\Lambda = -1$. Thus, observationally distinguishing a time variation in the equation of state or finding w_X different from -1 will rule out a pure cosmological constant as an explanation for the data, but be consistent with a dynamical solution.

Here let me mention few models, according to the expected values of their equation of state:

2.1 Topological Defects, $-1/3 \geq w_X \geq -2/3$

Dark energy can receive contributions from topological defects produced at phase transitions in the early universe (see e.g. ^{10, 11}). However, despite a well established theoretical framework, topological defects have not been thoroughly explored due to technical difficulties in the numerical simulations. More recently, a plausible version of dark energy made of a frustrated network of domain walls was proposed by ¹² (see also ¹³). These models have several appealing features: Firstly, topological defects are ubiquitous in field theory and unavoidable in models with spontaneously broken symmetries. Second, the scale of spontaneous symmetry breaking responsible for the walls is expected to lie in the $10 - 100 \text{ KeV}$ range and can arise naturally in supersymmetric theories (¹⁴). Finally a firm phenomenological prediction can be made for domain walls models: an equation of state strictly $-1/3 \geq w_X \geq -2/3$ (see e.g. ¹⁴). These models are therefore predictive in the value of the equation of state parameter and distinguishable from a cosmological constant even at zero order on w_X , (while, for example, scalar field models can also produce $w_X \sim -1$ although they differ from a cosmological constant which in the first order variation has $\dot{w}_X = 0$).

2.2 Scalar Fields - Quintessence $-2/3 \geq w_X \geq -1$

It is entirely possible that a dynamic mechanism is giving rise to the observed acceleration of the present Universe. Some of the popular proposed candidates to explain the observations are a slowly-rolling scalar field, "quintessence" ^{15, 16}, or a "k-essence" scalar field with non-canonical kinetic terms in the Lagrangian ^{17, 18}. An important property of these models is that, since the equation of state is time dependent, the fine tuning ("why now") problem can be in principle alleviated. Several models have been proposed and a complete study of all the related potentials goes well beyond the present 6-pages work. As mentioned, the most general prediction is a value for the equation of state $w(z)$ that differs from unity and varies with redshift z . A second way to distinguish between scalar field candidates is to measure the sound speed of the dark energy component that affects the perturbations in its energy distribution. The sound speed in many models of quintessence is equal to the speed of light, however can be different from

c , for example, in k-essence models, where it varies, triggered by the transformations in the background equation of state.

2.3 Phantom or Super-Quintessence, $-1 \geq w_X$

As we will see in the section, the present data does not rule out but even slightly suggest $w_X < -1$. Scalar field models with such equation of state (known as “phantom” or super-quintessence models) deserve a separate discussion since they cannot be achieved by scalar fields with positive kinetic energy term. The limitation to $w_X > -1$ is indeed a theoretical consideration motivated, for example, by imposing on matter (for positive energy densities) the null energy condition, which states that $T_{\mu\nu}N^\mu N^\nu > 0$ for all null 4-vectors N^μ . Such energy conditions are often demanded in order to ensure stability of the theory. However, theoretical attempts to obtain $w_X < -1$ have been considered^{19,20,22,23,21}. Unstable at quantum level, a careful analysis of their potential instabilities has been performed in²⁴. Moreover, the expansion factor of a universe dominated by phantom energy diverges in a finite amount of cosmic time, culminating in a future curvature singularity (Big rip²⁵ or Big smash²⁶ phase).

2.4 Chaplyngin gases $w_X = -1$ today, $w_X = 0$ yesterday

The Chaplyngin Gas (CG) (see e.g. ²⁷) provides an interesting possibility for an unified picture of dark energy and dark matter since such component interpolates in time between dust ($w_X = 0$) and a cosmological constant ($w_X = -1$), with an intermediate behavior as $p = \alpha\rho$. Perturbations of this fluid are stable on small scales, but behave in a very different way with respect to standard quintessence. Analysis of the effect of those perturbations on CMB and LSS data, in particular, have strongly constrained CG, disfavouring it as an unified dark matter candidate (see e.g. ²⁸).

3 Analysis of the current data.

In order to bound w_X , we consider a template of flat, adiabatic, X -CDM models computed with CMBFAST²⁹. We sample the relevant parameters as follows: $\Omega_{cdm}h^2 = 0.05, \dots, 0.20$, in steps of 0.01; $\Omega_b h^2 = 0.015, \dots, 0.030$ (motivated by Big Bang Nucleosynthesis), in steps of 0.001, $\Omega_Q = 0.0, \dots, 0.95$, in steps of 0.05 and $w_X = -3.0, \dots, -0.4$ in steps of 0.04, assumed as constant with redshift. For most of the dynamical models on the market, the assumption of a piecewise-constant equation of state is a good approximation for an unbiased determination of the effective equation of state (³⁹)

$$w_{\text{eff}} \sim \frac{\int w_X(a) \Omega_X(a) da}{\int \Omega_X(a) da} \quad (1)$$

predicted by the model. Hence, if the present data is not compatible with a constant $w_X = -1$, it may be possible to discriminate between a cosmological constant and a dynamical dark energy model.

The value of the Hubble constant in our database is not an independent parameter, since it is determined through the flatness condition. We adopt the conservative top-hat bound $0.45 < h < 0.85$ and we also consider the 1σ constraint on the Hubble parameter, $h = 0.71 \pm 0.07$, obtained from Hubble Space Telescope (HST) measurements³⁸.

We allow for a reionization of the intergalactic medium by varying the Compton optical depth parameter τ_c over the range $\tau_c = 0.05, \dots, 0.30$ in steps of 0.02.

For the CMB data we use the recent temperature and cross polarization results from the WMAP satellite (³⁰) using the method explained in (³¹) and the publicly available code on the LAMBDA

web site. As in ⁴, we further include the results from the BOOMERanG-98 ³², DASI ³³, MAXIMA-1 ³⁴, CBI ³⁵, VSAE ³⁶ experiments by using the publicly available correlation matrices and window functions. We consider 7%, 10%, 4%, 5%, 3.5% and 5% Gaussian distributed calibration errors for the BOOMERanG-98, DASI, MAXIMA-1, VSA, and CBI experiments respectively.

In addition to the CMB data we also consider the real-space power spectrum of galaxies in the 2dF 100k and SLOAN first year galaxy redshift survey using the data and window functions of the analysis of ³⁷ and ³. We restrict the analysis to a range of scales over which the fluctuations are assumed to be in the linear regime ($k < 0.1h^{-1}\text{Mpc}$). When combining with the CMB data, we marginalize over a bias b for each dataset considered to be an additional free parameter.

We finally incorporate constraints obtained from the luminosity measurements of Type Ia supernovae (SN-Ia) from ² using the GOLD dataset and again evaluating the likelihoods assuming a constant equation of state.

In Figure 1 we plot the likelihood contours in the (Ω_M, w_X) plane from our joint analyses of CMB+SN-Ia+HST+LSS data. As we can see, there is strong supporting evidence for dark energy. A cosmological constant with $w_X = -1$ is in good agreement with all the data. However the $2\text{-}\sigma$ confidence levels are $-1.32 < w_X < -0.82$ with a best-fit value of $w_X \sim 1.04$, slightly preferring “phantom” models.

While the analysis rules out topological defects as dark energy, it is important to note that this result is almost completely due to the inclusion of the Supernovae Type-Ia dataset. Topological defects can provide a good fit to the WMAP data for a different choice of priors with “lower” values of the Hubble parameter ($h < 0.65$), (as indicated by Sunyaev-Zeldovich and time delays for gravitational lensing observations), and “higher” values of the matter density ($\Omega_m > 0.35$), (in agreement with recent measurements of the temperature-luminosity relation of distant clusters observed with the XMM-Newton satellite) (see ⁴⁰).

A cosmological constant is compatible with our analysis but this result may be biased by the assumption of a constant with redshift equation of state. However, analysis of recent supernovae data, while still compatible with an evolution of w_X (see the contribution of M. Giavalisco), are not providing an evidence for such variation.

4 Conclusions

We have demonstrated that, even by applying the most current constraints on the dark energy equation of state parameter w_X , there is much uncertainty in its value. Interestingly, there is a distinct possibility that it may lie in the theoretically under-explored region $w_X < -1$. An observation of a component to the cosmic energy budget with $w_X < -1$ would naturally have significant implications for fundamental physics. Further, depending on the asymptotic evolution of w_X , the fate of the observable universe ^{41,44} may be dramatically altered, perhaps resulting in an instability of the spacetime ²⁴ or a future singularity.

If we are to understand definitively whether dark energy is dynamical, and if so, whether it is consistent with w_X less than or greater than -1 , we will need to bring the full array of cosmological techniques to bear on the problem. An important contribution to this effort will be provided by direct searches for supernovae at both intermediate and high redshifts ⁴⁵. Other, ground-based observations ⁴⁶ will allow complementary analyses, including weak gravitational lensing ⁴⁷ and large scale structure surveys ⁴⁸ to be performed.

At present, however, while the data remain consistent with a pure cosmological constant Λ .

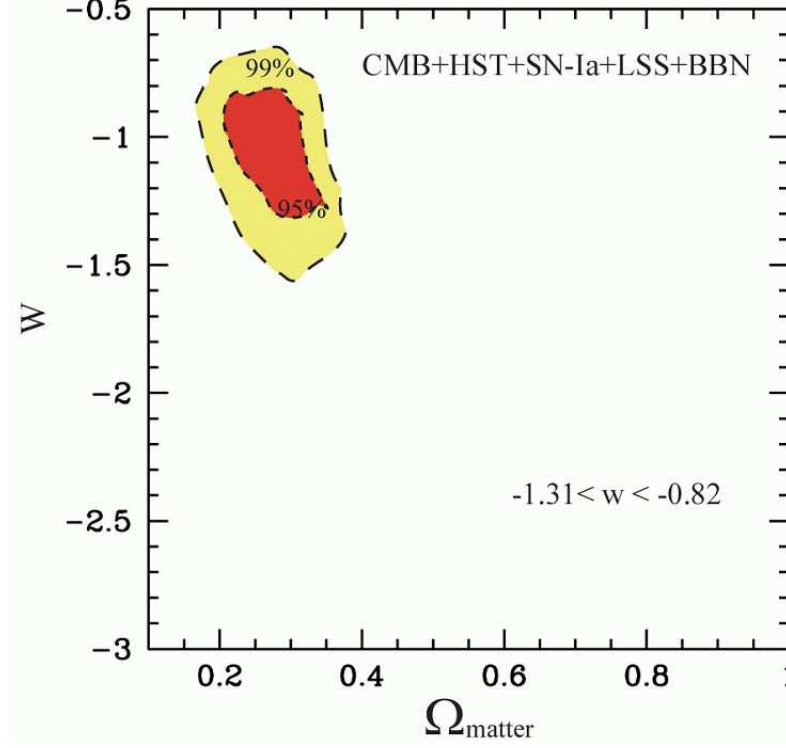


Figure 1: Likelihood contours in the (Ω_M, w_X) plane for the joint CMB+HST+SN-Ia+LSS analysis described in the text. We take the best-fit values for the remaining parameters. The contours correspond to 0.05 and 0.01 of the peak value of the likelihood, which are the 95% and 99% confidence levels respectively.

Acknowledgments

I would like to thank the organizers for this great conference on the italian Alps. I am indebted with my collaborators: Luca Conversi, Laura Mersini, Carolina Odman, Mark Trodden and Joe Silk.

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